7. Cost and Emission Reduction Analysis of HFC Emissions from Refrigeration and Air-Conditioning in the United States

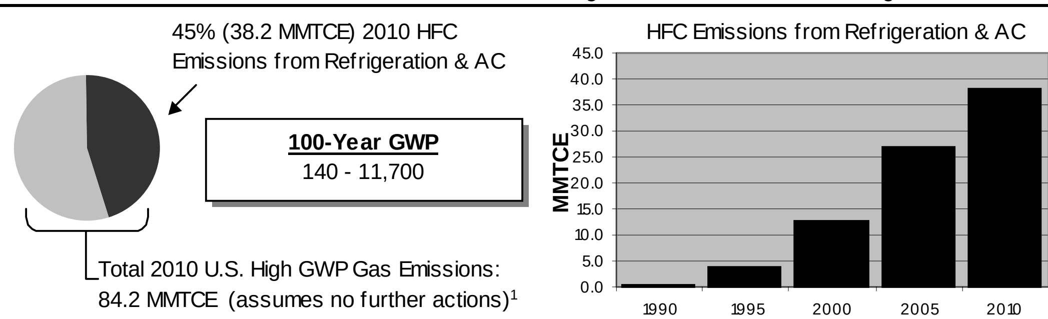
7.1 Introduction

A number of hydrofluorocarbons (HFCs) are used in refrigeration and air-conditioning systems that, when operated and repaired, result in the emission of HFCs. Specifically, emissions occur in product and equipment manufacturing, component failure, leaks and purges during operation, releases during servicing, releases from the disposal of equipment or used refrigerant containers and (illegal) venting of refrigerant. The use of refrigerant and air-conditioning equipment also generates "indirect" emissions of greenhouse gases (primarily carbon dioxide) from the generation of power required to operate the equipment. It is important to note that in many applications, these indirect emissions may outweigh the direct emissions from this sector in the U.S., and hence, gains in energy efficiency can have a major impact on the total emissions of an application. HFCs have global warming potentials (GWPs) that range from 140 to 11,700. The most commonly used HFC refrigerant, HFC-134a, has a GWP of 1,300 and an atmospheric lifetime of 14.6 years. According to the EPA's Vintaging Model projections, under a business-as-usual scenario the United States would emit about 38 million metric tons of carbon equivalent (MMTCE) of HFCs by 2010 from the refrigeration and air-conditioning sector assuming reduction efforts are not made (see Exhibit 7.1).[1]

In the United States, the refrigeration and air-conditioning sector includes nine major end uses:

- household refrigeration;
- domestic air-conditioning and heat pumps;
- motor vehicle air-conditioning (MVAC);
- chillers;

Exhibit 7.1: U.S. Historic and Baseline HFC Emissions from Refrigeration and Air-Conditioning



[1] A fuller explanation of the business-as-usual scenario under which baseline emissions are estimated appears in the Introduction to the Report.

- retail food refrigeration;
- cold storage warehouses;
- refrigerated transport;
- industrial process refrigeration; and
- commercial unitary air-conditioning systems.

Each end use is composed of a variety of different equipment types that have historically used ozone-depleting substances (ODS) such as chlorofluorocarbons (CFCs) or hydrochlorofluorocarbons (HCFCs). As the ODS phaseout is taking effect under the Montreal Protocol and Clean Air Act, equipment is being retrofitted or replaced to use HCFC- or HFC-based substitutes. In time, HCFCs are expected to be replaced with HFCs or other alternative refrigerants. A detailed discussion of the end uses that either currently use HFCs or are likely to use them in the near future is provided in Appendix 7.1.

7.2 Historical and Baseline HFC Emission Estimates

The EPA uses its Vintaging Model and data from industry in order to simulate the aggregate impacts of the ODS phaseout on the use and emissions of various fluorocarbons and their substitutes. The model tracks end uses of these gases over a period of 45 years across more than 40 different applications. The model uses the annual "vintages" of new equipment that enter service in each end use as the main driver of gas usage and emissions. The vintage of each type of equipment determines such factors as leak rate, charge size, number of units in operation, and the initial ODS that the equipment contained (see Appendix A for more information).

Commercial and industrial refrigeration and air-conditioning is one of the major end use categories defined in the Vintaging Model to characterize ODS substitute use in the United States. The Vintaging Model data for HFC emissions from 1990-2010 by substitute within the refrigeration and air-conditioning end uses are shown in Exhibits 7.2 and 7.3. The Vintaging Model's estimates of HFC emissions by end use within the refrigeration and air-conditioning sector for 2000-2010 are presented in Exhibit 7.4.

There are several regulatory programs in place (e.g., CAA §608 and §609 refrigerant recovery requirements) to regulate emissions of ODS substitutes in some applications. These programs are resulting in significant reductions of ODS substitute emissions. These reductions are incorporated in the baseline estimate. The cost analysis evaluates the cost of reducing emissions from this baseline.

HFC emissions are expected to be greatest in the motor vehicle air-conditioning (MVAC) and retail food end uses. Because HFC-134a has been the primary refrigerant used in automobiles manufactured since 1994, and because it is the primary refrigerant used to replace older CFC-12 systems, the amount of HFC emissions in motor vehicle air-conditioning units is expected to rise. Retail food systems are expected to transition at least in part to HFC-134a and HFC-containing blends, and due to certain equipment characteristics, such as their large charge size, often have higher refrigerant emission rates. Cold storage systems also use large charge sizes, but HFC emissions relative to other refrigeration and air-conditioning end uses are not expected to increase significantly. Emissions of HFCs from chillers are relatively low as a result of the continued use of HCFC-123 and the low leak rates of new HFC-134a units. The requirement to recover and recycle refrigerants during service and disposal is expected to reduce emissions across all of the end uses and is reflected in the baseline. Since commercial unitary and residential air-conditioning equipment has yet to transition into HFCs, the emissions of HFCs from these end uses before 2005 are estimated to be relatively insignificant.

Exhibit 7.2: Historical U.S. HFC Emissions from the Refrigeration and Air-Conditioning Sector (1990-1999)										
	1990	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**
Emissions (MMTCE)	0.2	0.2	0.4	1.4	2.6	4.0	5.8	7.5	9.4	11.0

Source: EPA, 2000 (for 1990-1998) and EPA estimates (for 1999).
Notes:
Emissions are not broken down by chemical to avoid disclosure of confidential business information.
Conversion to MMTCE is based on the GWPs listed in the Introduction to the Report.

Exhibit 7.3: Baseline U.S. HFC Emissions from the Refrigeration and Air-Conditioning Sector (2000-2010)			
	2000	**2005**	**2010**
Emissions (MMTCE)	12.7	27.0	38.2

Notes:
Emissions are not broken down by chemical to avoid disclosure of confidential business information.
Conversion to MMTCE is based on the GWPs listed in the Introduction to the Report.
Forecast emissions are based on a business-as-usual scenario, assuming no further action.

Exhibit 7.4: Baseline U.S. HFC Emissions by Refrigeration and Air-Conditioning End Use

	2000		**2005**		**2010**	
End Use	**Quantity (MMTCE)**	**% of Total**	**Quantity (MMTCE)**	**% of Total**	**Quantity (MMTCE)**	**% of Total**
MVACs	7.3	57	15.8	58	16.9	44
Retail Food	2.6	20	4.6	17	9.8	26
Residential A/C	0.1	1	1.4	5	4.6	12
Refrigerated Transport	1.2	9	2.5	9	2.9	8
Chillers	1.1	9	1.5	6	1.4	4
Industrial Process	0.2	2	0.6	2	1.1	3
Commercial A/C	0.0	0	0.3	1	0.9	2
Cold Storage	0.1	1	0.3	1	0.5	1
Other Appliances	0.1	1	0.2	1	0.2	1
Total	**12.7**		**27.0**		**38.2**	

Notes:
About 75% of emissions are from the retail food and motor vehicle air-conditioning sectors.
Sums might not add to total due to independent rounding.

7.3 HFC Emission Reduction Opportunities

HFC emissions from refrigeration and air-conditioning equipment can be reduced through a variety of technology and practice options. Although some of the options considered in this report may be implemented in the baseline in response to the requirements of existing or proposed regulatory programs, many would entail voluntary action by the private sector. Some of the most widely recognized approaches to reduce refrigerant emissions include:

- maintenance and leak detection to reduce refrigerant leakage (required under existing law);
- technician certification (required under existing law);
- increasing recovery, recycling, and reclamation (required under existing law);
- ensuring proper refrigerant disposal (required under existing law); and
- use of alternative refrigerants and refrigeration and air-conditioning technologies (UNEP, 1998).

Reducing Leak Rates

Several different approaches can be used to reduce leak rates (EPA, 1995; EPA, 1998a). Although some of the options available for existing equipment may be impractical for in-place equipment given the difficulty and expense of retrofitting, there are still many available options that are currently used and economically feasible. Some approaches involve reducing joint failures. There are a number of other leak reduction options used in current industry practice, including:

- use of preventive maintenance, including leak detection;
- broader use and improvement of brazing techniques rather than threaded or snap fittings (e.g., use of sufficient silver content, and use of dry nitrogen or other inert gas to avoid oxidation);
- focus on ensuring accessibility to field joints and use of isolation valves, which allow for greater ease of repair;
- focus on proper securing to reduce vibration fractures in the pipe and connections from the compressor and other moving parts of the system;
- repairing or retrofitting high-emitting systems through targeted component upgrades; and
- performing major modifications to the systems.

As can be seen from this list, leak reduction approaches range from simple repairs of short duration to major, long-lasting system repair jobs. Replacement of high-emitting fittings is one of the most technically and economically feasible approaches that can be used to reduce refrigerant leakage. Although leak reduction is already required by law, leak reduction projects could be more extensive, such as the replacement or upgrade of a major system component.

Technician Certification

As required by law, technicians must be certified to purchase CFC and HCFC refrigerants and service refrigeration and air-conditioning equipment. In 1998, EPA proposed extending these regulations to HFC refrigerants as well. By ensuring that technicians receive training in the recovery and recycling of refrigerant, refrigerant emissions will be reduced.

Recovery and Recycling

Recovery and recycling of refrigerant has already helped to decrease emissions of refrigerants during equipment service and disposal in the United States and has led to reductions in HFC emissions. The approach involves use of a refrigerant recovery device that transfers refrigerant into an external storage container prior to servicing of the equipment. Once the recovery process and source operations are complete, the refrigerant contained in the storage container may be recharged back into the equipment, cleaned through the use of recycling devices, sent to a reclamation facility to be purified, or disposed of through the use of incineration technologies. Recycling cleans and reclamation purifies recovered refrigerant; reclamation is more thorough and involves repeated precision distillation, filtering, and contaminant removal. Refrigerant recovery may also be an important way to reduce emissions from near-empty refrigerant containers (i.e., can heels). Refrigerant recovery is widely practiced under EPA regulations pursuant to the Clean Air Act Amendments and is therefore not analyzed further here.

Proper Refrigerant Disposal

One potential source of emissions from the refrigeration and air-conditioning sector in the United States is the accidental venting of contaminated refrigerant. One method to reduce venting of such refrigerant is to increase the reclamation of used refrigerant and properly dispose of the refrigerant that cannot be reclaimed

(UNEP, 1999). The cost to dispose of refrigerant, including transportation and storage, is estimated to be between $1.50 and $5.00 per pound, depending on the quantity purchased (ICF Consulting, 2000). Proper refrigerant disposal is required by existing law and is therefore not analyzed further here.

Replacement Options

In addition to the emission reduction approaches that may be required by existing law and EPA regulations, there are several potential ODS replacement options that could be used in place of HFC-containing equipment in the United States. These include secondary loop systems, distributed systems, and ammonia- or hydrocarbon-based systems. Such technological changes may also reduce charge size, which will in turn reduce emissions. Some of these alternative refrigerants and technologies have not been commercialized, but may become more feasible with research and development (Dieckmann and Magid, 1999). Alternative refrigerants and equipment designs are described in Appendix 7.2.

7.4 Cost Analysis

There are technically feasible opportunities for reducing HFC emissions from the refrigeration and air-conditioning sector. It is anticipated that the most cost-effective approaches, including leak reduction, refrigerant recovery, and proper refrigerant disposal, will be implemented under EPA regulatory programs. The main factors affecting the feasibility of implementing certain replacement options include designing new alternative-refrigerant systems that meet the strict requirements for protection of human health and the challenge of designing system components that are compatible with substitute refrigerants (UNEP, 1999). Exhibit 7.5 presents emission reduction technologies and practices. Appendix 7.2 provides additional information on the technical issues associated with developing refrigeration and air-conditioning systems that use non-HFC refrigerants.

The more promising emission reduction opportunities include: [2]

- Ammonia and hydrocarbon systems and state-of-the-art emission reduction technology are feasible for new industrial process refrigeration systems. For cold storage and retail food systems, replacing existing equipment with equipment that uses non-HFC refrigerants can be quite expensive, although the total emission reduction could be substantial (UNEP, 1999). For these end uses, most emission reduction opportunities for existing equipment will involve focusing on minor and major repairs of high-emitting fittings and faulty components.
- Replacing leaking components and repairing weak joints, as is required by law for large systems, has the potential to reduce HFC emissions to a significant degree, especially in large systems such as chillers, cold storage warehouses, and retail food systems that could leak large amounts of refrigerant. Regular monitoring of refrigeration and air-conditioning systems to check for leaks will prevent the loss of refrigerant. Many efforts to reduce leakage will be made under compliance with proposed regulatory requirements. Voluntary private sector initiatives to reduce leakage further than required under regulation are also feasible.

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[2] One of the more promising replacement options may be the introduction of new refrigerants that can be used in existing HFC systems. Currently, ammonia and hydrocarbons are viable options for certain applications, but for the majority of traditional HFC systems, major design modifications would be required, and in some systems, safety concerns may violate fire codes, negating this as an option entirely. Recently, the EPA Significant New Alternatives Policy (SNAP) program has been considering the acceptability of non-ammonia refrigerant blends that have significantly lower GWPs than the currently available HFCs. However, due to insufficient data, such potential alternative refrigerants were not considered in this analysis.

- Replacing HFC direct expansion systems with HFC distributed systems in retail food settings offers the potential to reduce HFC emissions. Distributed systems have smaller refrigeration units distributed among the refrigerated and frozen food display cases, with each unit sending heat to a central water cooling system. A distributed system would significantly reduce the refrigerant inventory and minimize the length of refrigerant tubing and the number of fittings that are installed in direct expansion systems, thereby reducing leaks of HFCs (Dieckmann and Magid, 1999).
- Designing new retail food and cold storage systems to operate using secondary loops with HFCs or alternative refrigerants such as ammonia can reduce HFC emissions. Secondary loop systems circulate a secondary coolant or brine from the central refrigeration system to the display cases, isolating customers from the refrigerant (UNEP, 1999; Dieckmann and Magid, 1999). These systems have lower leak rates and operate at reduced charges. Other positive features of this technology include longer shelf life, enhanced reliability, more efficient defrost, and less maintenance required than conventional direct expansion systems. Additionally, pipes used in these systems are now pre-manufactured and can be made of pre-insulated plastic instead of copper. This reduces material costs and, by eliminating the need for brazing, allows for faster installation. In recent years, installation costs have been reduced by more than 25 percent. With continued research and development, it is expected that this technology will soon be as cost-effective to purchase, install, and operate as direct expansion systems (Bennett, 2000).
- Several HFC-alternative refrigerants are being researched and developed, including: (1) carbon dioxide or hydrocarbon secondary loop systems in motor vehicle applications; (2) hydrocarbon systems for residential refrigeration equipment; and (3) hydrocarbons in hermetic systems for residential applications.
- Geothermal cooling systems for residential and commercial spaces are becoming increasingly popular and economically sound as an alternative to conventional air-conditioning systems. Geothermal technology transfers heat between the system and the earth and can provide both space heating and cooling. Though installation costs are typically 30 to 50 percent higher than conventional systems, incremental costs are reduced by 20 to 40 percent, due in large part to increased energy efficiency. Economic paybacks can accrue in as little as three to five years. Geothermal systems may save homeowners 20 to 50 percent in cooling costs (Geoexchange, 2000; Rawlings, 2000). Due to lack of cost and market penetration data, this technology is not considered further in this analysis.

Estimating Costs of Reducing HFC Emissions

To develop estimates of the costs of reducing HFC emissions through implementation of the non-regulatory mitigation options, preliminary estimates of incremental capital and operating costs were developed.[3] Most of the readily available data focused on the costs and emission reductions for recovery and leak reduction operations.[4] Using information available for select equipment modification and

[3] In some cases incremental cost data are not available given that the technologies have not been commercialized.

[4] In the United States, substantial reductions in emissions of HFCs from the refrigeration and air-conditioning sector can be achieved at low cost. The most cost-effective approaches include increasing recovery rates and reducing leakage rates. Preliminary data gathered from industry in support of EPA regulatory efforts indicate that leakage rates for certain types of existing equipment range from 8 to 40 percent, whereas achievable leak rates for new or modified equipment can be between 7 to 15 percent. Some experts suggest that through additional design and practice changes, leakage could be reduced to as low as 2 to 5 percent in the future. Recovery of refrigerants during servicing or disposal can be profitable in many cases, especially for equipment with very large charge sizes. Preventing the servicing of motor vehicle air conditioners by individuals that lack the tools and skills to recover refrigerant (also a proposed regulatory requirement), and increasing rates of refrigerant recovery during equipment disposal can also lead to substantial reductions in emission at a relatively low cost.

replacement options, a spreadsheet model was used to estimate the break-even refrigerant price (i.e., the refrigerant price that would offset the investment in the practice or technology to reduce emissions). Specifically, a discounted cash flow analysis was performed for each emission reduction option to estimate the refrigerant price that would offset the cost of the emission reduction option. Then the carbon-equivalent value was determined by subtracting the break-even price from the refrigerant market price and converting to a metric ton of carbon equivalent (TCE) basis. Finally, preliminary estimates of the potential emission reduction for each technology or practice by end use were developed. These potential emission reductions are expressed as a percent reduction of the baseline emission estimates from the Vintaging Model for 2010.

Analysis of Indirect Emissions and Associated Costs. In addition to direct emission reductions that result from decreased leak rates and/or charge sizes associated with alternative technologies and/or refrigerants, emissions during manufacture and from energy use were also factored into the break-even refrigerant price. Emissions during manufacture, including the energy consumed and fugitive emissions, were calculated based on the methodologies described in Appendix A of Dieckmann and Magid (1999).

Information on relative energy efficiency was used to estimate changes in annual energy costs and changes in greenhouse gas emissions that result from an increase or decrease in electricity generation, relative to conventional technologies used in each end use. In calculating indirect emissions, each kilowatt hour (kWh) of energy consumption was assumed to emit the equivalent of 0.64 kilograms (kg) of carbon dioxide, the national average emissions from power plants (Sand *et al*., 1997). Indirect costs from energy consumption were assumed to be $0.06/kWh, the average energy cost projected for the year 2010 (EIA, 2000).

Analysis of Net Emissions and Costs. Once direct and indirect emissions were determined, they were factored into net emission and cost calculations accordingly. If indirect emissions exceeded direct emission reductions associated with a given alternative technology and/or refrigerant, the option was not analyzed further. Where net emissions were still achieved, indirect emissions were subtracted out, and additional energy costs were considered in the cost analysis. Similarly, where a particular option resulted in increased energy efficiency and therefore decreased indirect emissions, the associated emission savings were added in, and cost savings were factored into the cost analysis.

A financial screening analysis was also conducted to determine if costs would likely exceed $200/TCE. Replacement options that resulted in net emission reductions but yielded carbon costs that exceeded $200 were not considered. These included:

- hydrocarbons in secondary loop for residential applications;
- hydrocarbons in secondary loop for motor vehicle air-conditioning applications; and
- carbon dioxide in motor vehicle applications.

Exhibit 7.5: Cost, Duration, and Applicability of Emission Reduction Options

Technology/Practice Description	Estimated Incremental Cost($)	Duration of Emission Reduction (years)	Potential Applicability to End Use Equipment								
			Chillers	Retail Food	Cold Storage Warehouses	Refrigerated Transport	Industrial Process Refrigeration	Commercial Unitary A/C	MVAC	Residential A/C	Household Refrigeration
Practice											
Recovery of refrigerant[a]	10 to 3,000[b]	1	✓	✓	✓	✓	✓	✓	✓	✓	✓
Minor repair[c]											
Minor leak reduction technology	5 to 275[b]	1	✓	✓	✓	✓	✓	✓	✓	✓	
Replacement of high-emitting fittings	600	5	✓	✓	✓	✓	✓	✓	✓	✓	
Major repair[c]											
Replacement or upgrade of major system component	800 to 1,400	5	✓	✓	✓	✓	✓	✓	✓	✓	
Major modification of the equipment	6,000 to 12,000	< 7 to 10	✓	✓	✓		✓	✓		✓	
Replacement Options: Alternative Refrigerants											
Replacement with equipment that uses ammonia as refrigerant	-	Lifetime of equipment		✓	✓		✓				
Replacement with system that uses hydrocarbon refrigerant[d]	-	Lifetime of equipment				✓	✓		✓		✓
Replacement with CO_2 refrigeration[e]	-	Lifetime of equipment				✓			✓		
Replacement Options: Alternative Refrigeration Technologies											
Replacement with distributed system	-	Lifetime of equipment		✓	✓						
Replacement with desiccant cooling system	-	Lifetime of equipment	✓					✓	✓	✓	
Replacement with absorption system	-	Lifetime of equipment	✓				✓	✓		✓	
Replacement with secondary loop system	-	Lifetime of equipment		✓	✓				✓		

Notes:
- Not provided given the variability in state of technology commercialization across the end uses (see Section 7.4).
[a] Refrigerant recovery will be widely practiced under the requirements of EPA regulatory initiatives.
[b] The wide range in the estimated incremental cost for these readily-available technologies reflects the fact that a variety of equipment types are being considered in this analysis.
[c] Many efforts to reduce leakage will be made under compliance with proposed regulatory requirements. Voluntary private sector initiatives to reduce leakage further than required under regulation are feasible.
[d] Systems that use hydrocarbon refrigerants may technically be used as replacements for the chiller, retail food, and cold storage warehouse end uses, but their large charge sizes raises safety and liability concerns. Therefore, this option was not considered further in this analysis.
[e] Research and development efforts to design CO_2 systems for stationary equipment (e.g., chillers) are being pursued, but industry experts do not believe that this technology will be a major replacement option within the time period of this analysis.

Although the cost of replacing HFCs with carbon dioxide in motor vehicle applications is greater than \$200/TCE and is not studied further, it is important to note that this option represents a potentially significant reduction opportunity. Furthermore, carbon dioxide in motor vehicle applications may provide other benefits such as improved comfort. This analysis suggests that, by 2010, this application would eliminate 17 MMTCE, equivalent to 44 percent of the total HFC emissions from the refrigeration and air-conditioning sector.

Exhibit 7.6 presents the indirect emissions and net emissions calculated for the three most viable replacement options—distributed systems, ammonia secondary loop systems, and HFC secondary loop systems. The analysis compared these emission reduction technologies to a prototypical technology, the direct expansion (DX) system that uses HFCs. DX systems consume an average of 1,200,000 kWh per year and emit an average of 209 TCE (Dieckmann and Magid, 1999). Incremental capital costs for replacement systems were based on the following data provided by industry experts:

- direct expansion systems (base) = \$200 per ton of cooling capacity to install;
- HFC distributed system = 50 percent more expensive;
- HFC secondary loop system = 20 percent more expensive; and
- ammonia secondary loop system = 75 percent more expensive.

It was assumed that the incremental capital costs for ammonia systems included expenditures for equipment needed to ensure safety. The incremental operating costs only included the net energy requirements and did not cover costs associated with training of technicians and development and updating of safety protocols to handle more hazardous refrigerants such as ammonia.

Exhibit 7.6: Net Annual Emissions and Energy Costs of Replacement Options

	DX System (Base)	Distributed System	Ammonia Secondary Loop System	HFC Secondary Loop System
Charge Size (kg)	1633	408	180	180
HFC Leak Rate (% of charge/yr)	15%	4%	0%	2%
Direct Emissions (kg/yr)	245	16	0	4
Change in Direct Emissions (kg/yr)	N/A	(229)	(245)	(241)
Change in Direct Emissions (TCE/yr)	N/A	(204)	(218)	(214)
Energy Consumption (kWh/yr)	1,200,000	1,100,000	1,400,000	1,400,000[a]
Indirect Emissions (TCE/yr)[b]	209	192	244	244
Relative Indirect Emissions: Change in Indirect Emissions (TCE/yr)	N/A	(17)	35	35
Total Net Emissions (TCE/yr)	**N/A**	**(221)**	**(183)**	**(179)**
Net Electricity Cost (\$/yr)[c]	**N/A**	**(\$6,000)**	**\$12,000**	**\$12,000**

Source: Dieckmann and Magid, 1999.
Notes:
[a] Recent studies on low-charge refrigeration for supermarkets conducted by David Walker of Foster Miller suggest that secondary loop systems with improved technological features can lead to significant reductions in energy consumption (Walker, 2000a).
[b] Assumes a national average emissions factor of 0.64 kg CO_2/kWh (Sand *et al*., 1997).
[c] Assumes that energy costs are \$0.06/kWh.

Based on the analysis, only the distributed system results in a reduction of indirect emissions (of 17 TCE) and an electricity cost savings (of \$6,000/year). Both the ammonia and HFC secondary loop systems require additional energy use, resulting in increased indirect emissions of 244 TCE and increased electricity costs of \$12,000 on a yearly basis. However, it should be noted that recent technological advancements to HFC secondary loop systems have greatly augmented their energy efficiency, though these technologies are not yet economically competitive. With continued research and development and increased popularity and sales, the costs of this technology are expected to decrease in the near future. The additional energy costs of secondary cooling systems shown in Exhibit 7.6 may be offset by other advantages afforded by these systems, such as decreased maintenance costs, lower refrigerant replacement costs, and longer shelf lives (Walker, 2000b; Bennett, 2000).

Results

Exhibit 7.7 presents preliminary estimates of the costs and emission reductions for the mitigation options considered in this analysis. Exhibit 7.7 does not include costs and emission reductions for mitigation options that are required under regulations. Cost analyses were conducted for the following mitigation options: replacing direct expansion systems with distributed systems; repairing or replacing high-emitting fittings; replacing HFC systems with HFC secondary loop systems; and replacing HFC systems with ammonia secondary loop systems. The cost analyses were performed for four- and eight-percent discount rates, both with a ten-year project lifetime. Exhibit 7.7 summarizes HFC emission reductions by cost per metric ton of carbon equivalent (TCE). As shown, 12 percent of refrigerant emission reductions from the baseline can be achieved in 2010, at costs below $200 per TCE.

Replacing Direct Expansion Systems with Distributed Systems. This option was assumed to penetrate between 10 and 20 percent of the retail food and between 10 and 20 percent of the cold storage refrigeration markets, at a cost of $0.02/TCE and $7.21/TCE for four and eight percent discount rates, respectively. Based on this assumption, incremental emission reductions of four percent of the 2010 baseline are projected, equivalent to 1.5 MMTCE. This represents the most significant cost-effective option for reducing HFC emissions in the refrigeration and air-conditioning sector.

Leak Reduction Options. It was assumed that the various leak reduction options would penetrate 10 percent of the retail food and industrial process markets, and five percent of the chillers, cold storage, commercial air-conditioning, residential air-conditioning, and motor vehicle air-conditioning sector markets. This option is estimated to reduce emissions by 1.2 MMTCE, three percent of the total baseline emissions by 2010, at a cost of $3.58/TCE and $5.08/TCE for four percent and eight percent discount rates, respectively.

Replacing HFC System with HFC Secondary Loop System. This alternative was assumed to penetrate 10 to 20 percent of the retail food refrigeration market and 10 to 20 percent of the cold storage refrigeration market. It is estimated to reduce emissions by 1.5 MMTCE, or four percent of baseline emissions by 2010, at a cost of $62.57/TCE and $65.30/TCE for four and eight percent discount rates, respectively.

Replacing HFC System with Ammonia Secondary Loop System. This alternative, at a cost of $98.61/TCE and $108.67/TCE for four percent and eight percent discount rates, respectively, was estimated to penetrate ten percent of the retail food, ten percent of the cold storage, and ten percent of industrial process refrigeration sectors. This alternative would lead to a one percent incremental emission reduction, or 0.6 MMTCE.

Exhibit 7.7: Emission Reductions and Costs in 2010						
Option	Break-even Cost ($/TCE) Discount Rate		Incremental Reductions		Sum of Reductions	
	4%	8%	MMTCE of 2010 Base	Percent Reduction from 2010 Base	MMTCE	Percent of Baseline Emissions
Replace DX with Distributed System	0.02	7.21	1.5	4%	1.5	4%
Leak Reduction Options[a]	3.58	5.08	1.2	3%	2.7	7%
Replace HFC with HFC Secondary Loop System[b]	62.57	65.30	1.5	4%	4.2	11%
Replace HFC with Ammonia Secondary Loop System[b, c]	98.61	108.67	0.6	1%	4.8	12%

Notes:
[a] See Exhibit 7.5 for available leak repair options. To be conservative, this analysis used the highest cost option of replacing or upgrading a major system component , with an upper cost range of $1,400. Emissions are reduced over five years. Potential energy savings associated with leak reduction are not considered in this analysis but may slightly reduce break-even costs.
[b] Cost estimate derived from Smithart (2000) and Dieckmann & Magid (1999).
[c] Ammonia systems may be feasible for certain new equipment applications in the retail food and cold storage end uses. Range for ammonia system costs is based on estimates provided by Smithart (2000) and Dieckmann & Magid (1999). Estimated incremental costs range from $50-200/MT of cooling capacity.
2010 baseline HFC emissions from refrigeration and air-conditioning end uses equal 38.2 MMTCE.
Conversion to MMTCE is based on the GWPs listed in the Introduction to the Report.
Total might not sum due to independent rounding.

7.5 References

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Appendix 7.1: Refrigeration and Air-conditioning End Uses

Household Refrigeration

The household refrigeration end use consists of household refrigerators and freezers. HFC-134a is the primary substitute for CFC-12 in domestic refrigeration units, and most new household refrigerators are manufactured to use HFC-134a. The charge size of a typical household refrigeration unit is 0.32 kilograms, and its expected lifetime is 20 years. There are more than 150 million household refrigerators in the United States, and although this end use is one of the largest in terms of the number of units in use, the charge sizes are small. Because the units are hermetically sealed and rarely require recharging, emissions are relatively low. Since household refrigeration units have very low leak rates, the potential for reducing emissions through leak reduction is small. The retirement of old refrigerators is also not expected to result in significant HFC emissions, as U.S. regulation requires that refrigerants be recovered from appliances before disposal. This regulation is enforced by penalties of up to $25,000 for disposal companies in violation.

Residential Air-conditioning and Heat Pumps

Residential air-conditioning (window units, unitary air conditioners, packaged terminal air conditioners) and heat pumps are another source of HFC emissions from the residential sector. Most of these units are window units and central air conditioners. The charge sizes of the equipment in this sector tend to be small, on the order of 0.5 to 10 kilograms, and the average lifetime of equipment is 15 years. Residential and commercial air-conditioning is relying exclusively on HCFC-22 as the refrigerant until it is phased out for this use. R-410A (refer to Exhibit 7.8 for blend composition) is expected to replace HCFC-22 in new equipment for most end uses once HCFC-22 is phased out under the Clean Air Act. R-407C is expected to replace HCFC-22 mainly in retrofit applications.

Exhibit 7.8: Composition of Refrigerant Blends

Blend	Chemical Components	Ratio of Components
R-401A	HCFC-22, HCFC-124 & HFC-152	53:34:13
R-402A	HCFC-22, HFC-125 & propane	38:60:2
R-404A	HFC-125, HFC-134a & HFC-143a	44:4:52
R-407C	HFC-32, HFC-125 & HFC-134a	23:25:52
R-408A	HCFC-22, HFC-125 & HFC-143a	46:7:47
R-409A	HCFC-22, HCFC-124, HCFC-142b	60:25:15
R-410A	HFC-32 & HFC-125	50:50
R-502	CFC-115 & HCFC-22	51:49
R-507A	HFC-125 & HFC-143a	50:50

Source: EPA, 1998b.

Motor Vehicle Air-conditioning

Motor vehicle air-conditioners refer to the air-conditioning systems contained in motor vehicles (i.e., cars, trucks, and buses). The quantity of refrigerant contained in a typical car air-conditioner is approximately one kilogram (typically from 1 to 1.2 kilograms for pre-1994 model vehicles containing CFC-12 systems, and an average of 0.8 kilograms for newer vehicles containing HFC-134a systems) (Atkinson, 2000). The expected lifetime of MVAC units is about 12 years. Refrigerant use in this sector is significant because there are more than 160 million motor vehicles with operational air conditioners in the United States

(Atkinson, 2000). CFC-12 was the refrigerant used in MVACs until 1994, after which all air conditioners installed in new automobiles made the switch to HFC-134a. HFC-134a is also used as a retrofit chemical for existing CFC-12 systems (UNEP, 1998). Currently, there are an estimated 50 million vehicles that still operate using CFC-12 refrigerant (Atkinson, 2000). A variety of HCFC/hydrocarbon refrigerant blends are approved as replacements for CFC-12 in motor vehice air-conditioners, but these blends have captured only a small and declining share of the retrofit market. Possible alternatives to HFC-134a systems include transcritical carbon dioxide systems and flammable hydrocarbon or HFC-152a systems, which are both under study and development (SAE, 2000).

Chillers

Chillers are used to regulate the temperature and reduce humidity in offices, hotels, shopping centers, and other large buildings. The three primary types of chillers are centrifugal, reciprocating, and screw— each of which is named for the type of compressor employed. Chillers are long-lasting relative to most air-conditioning and refrigeration equipment. Most operating chillers will remain in service for more than 20 years and some will last 30 years or more. The charge size of a chiller ranges from 25 (reciprocating) to 1,800 kilograms (centrifugal). Large capacity centrifugal and screw chillers account for over 150,000 units in the United States (EPA, 1998a). HCFC-123 is the refrigerant of choice both for use in new low-pressure chillers and as a retrofit option for existing CFC-11 units. Production of HCFC-123 will continue until 2030, and recycled and recovered amounts will continue to be used thereafter. The market of CFC-12 high-pressure chillers is being replaced by HFC-134a. New chillers using HFC-134a are commercially available and the market for these machines has been very strong. HFC-245fa is a potential refrigerant for use in new low-pressure chillers to replace HCFC-123, and possibly in high-pressure chillers, to replace HFC-134a. However, commercialization of this technology is not likely to occur in the next ten years or so. High-pressure chillers that currently use HCFC-22 will be replaced by several HFC refrigerant blends and HFC-134a chillers. Likewise, most existing CFC-114 chillers will be replaced with new HFC-236fa chillers, for use primarily in specialty applications on ships, submarines, and nuclear power plants.

Retail Food Refrigeration

Retail food refrigeration includes refrigerated equipment found in supermarkets, convenience stores, restaurants, and other food service establishments. This equipment includes small reach-in refrigerators and freezers, refrigerated display cases, walk-in coolers and freezers, and large parallel systems. Charge sizes range from 6 to 1,800 kilograms, with a lifetime of 15 to 20 years. There are about 1.6 million retail food refrigeration systems in the United States (EPA, 1998a). Convenience stores and restaurants typically use stand-alone refrigerators, freezers, and walk-in coolers. In contrast, supermarkets usually employ large parallel systems that connect many display cases to a central condensing unit by means of extensive piping. Because the piping required for connection of all the cases can be miles long, these systems contain very large refrigerant charges.

During the earlier phases of the CFC phaseout, the use of HCFC-22 in retail food refrigeration was expanded considerably. Today, most existing retail food equipment is retrofitted with HCFC-based blends, although HFC blends are also used. New retail food equipment uses HFC blends such as R-404A and R-507A (see Exhibit 7.8).

Cold Storage Warehouses

Cold storage warehouses are used to store meat, produce, dairy products, and other perishable goods. There are about 2,000 cold storage warehouses in the United States. The expected lifetime of a cold storage warehouse is 20 to 25 years, and charge sizes are about 4,000 kilograms. New warehouses that would have used CFC-12 and R-502 as the refrigerant are expected to use HCFC-22 and HFC-134a as replacements in new equipment. Eventually, R-404A and R-507A are expected to replace HCFC-22 in new warehouses upon implementation of the HCFC phase-out (see Exhibit 7.8). Existing CFC-12 cold storage warehouses can be retrofitted with R-401A as a replacement refrigerant, and existing R-502 warehouses can be retrofitted with R-402A. Not all cold storage warehouses currently use CFCs or their replacements.

Refrigerated Transport

The refrigerated transport end use includes refrigerated ship holds, truck trailers, railway freight cars, and other shipping containers. This end use is one of the smallest because the average charge sizes are relatively small (7 to 8 kilograms) and less than one million refrigeration units are currently in use. The expected lifetime of a refrigerated transport system is 12 years. Trailers, railway cars, and shipping containers are commonly charged with HFC-134a, R-404A, and HCFC-22 (UNEP, 1999). Ship holds, on the other hand, rely on HCFC-22 (UNEP, 1999) and ammonia. In addition to HFC-134a, R-404A can also be used in new equipment (see Exhibit 7.8). Existing equipment can be retrofitted with R-401A and R-404A. In addition, transport refrigeration equipment includes systems that operate based on the evaporation and expansion of liquid carbon dioxide or nitrogen.

Industrial Process Refrigeration

Industrial process refrigeration includes complex, often custom-designed, refrigeration systems used within the chemical industry, petrochemical industry, pharmaceutical industry, oil and gas industry, metallurgical industry, and sports and leisure facilities. Charge size ranges on average from 650 to 9,100 kilograms, and average lifetime is 25 years. There are approximately 7,000 industrial process refrigeration systems in the United States (EPA, 1998a). Ammonia, hydrocarbons, HCFC-123, and HFC-134a are expected to be the most widely used substitute refrigerants for new equipment (UNEP, 1999). Upon completion of the HCFC phaseout, HFC-134a is expected to be the primary refrigerant.

Commercial Unitary Air-conditioning

Commercial unitary air-conditioning systems have relatively small charge sizes of about 9.5 to 34 kilograms. The expected lifetime of a commercial unitary air-conditioning unit is 15 years. There are approximately 2.5 million commercial unitary air-conditioning units in use in the United States (EPA, 1998a). R-407C, R-410A, and HFC-134a are expected to be the refrigerants used to replace HCFC-22 in new equipment upon implementation of the HCFC phaseout in the United States (see Exhibit 7.8).

Appendix 7.2: Alternative Refrigerants and HFC Emission Reduction Technologies

Alternative Refrigerants

Ammonia. Ammonia, primarily used in water cooled chillers, has excellent thermodynamic properties and can be used in many types of systems. In addition, it has the advantage of having a strong odor, which makes refrigerant leaks easier to detect, and is lighter than air, facilitating dispersion in the event of a release (UNEP, 1999). However, it must be used carefully, because it is toxic and slightly flammable. Ammonia is an explosion hazard at 16 to 25 percent in air, which creates a problem in confined spaces. Chillers using ammonia as a refrigerant are commercially available in Europe, and they have efficiencies that are comparable to or better than those of HFC-134a chillers. However, building and fire codes restrict the use of ammonia in the urban areas of the United States and many other countries. These safety concerns and institutional barriers effectively limit the potential for expanded use of ammonia chillers (Sand *et al*., 1997).

While the use of ammonia within public spaces such as supermarkets is limited in the United States by building codes and ordinances, it is a potential alternative for supermarkets if safety concerns can be adequately addressed through engineering design such as secondary loops and isolation. Indeed, modern ammonia systems in the United States are fully contained closed-loop systems with fully integrated controls that regulate pressures throughout the system. Also, all systems are required to have an emergency diffusion system and a series of safety relief valves to protect the system and its pressure vessels from over-pressurization and possible failure (ASHRAE, 1993). Systems with ammonia are being built and used in Europe (Sand *et al*., 1997). However, the further use of ammonia as a supermarket primary refrigerant may be unlikely in the near future in the United Kingdom and other countries because of the capital costs and issues of compliance with standards and safety regulations (Cooper, 1997). Ammonia would also be an option in some industrial process refrigeration, contingent upon addressing all of the relevant concerns regarding flammability and toxicity.

The chemical properties of ammonia make it incompatible with current designs of residential light commercial unitary air-conditioning systems, which use copper for the refrigerant tubing, in the heat exchangers and in other components. Ammonia in the presence of water cannot be used with copper or zinc (UNEP, 1999); however, ammonia can be used in aluminum and steel systems. Compatible components would have to be developed to use ammonia. As a result of these technical and cost barriers, as well as ammonia's flammability and toxicity, ammonia is considered an unlikely candidate for use in commercial residential unitary equipment (Sand *et al*., 1997).

Hydrocarbons. Hydrocarbons have thermodynamic properties that make them good refrigerants; however, their high flammability causes concern for safety. Considering technical requirements only, there is potential for use of hydrocarbons in retail food refrigeration, transport refrigeration, household refrigeration, residential air-conditioning, mobile air-conditioning, and commercial unitary systems. Currently used refrigerants include HC-600a, HC-290, and HC-1270 (UNEP, 1999). In addition to good thermodynamic properties, hydrocarbons also have other advantages such as high energy efficiencies, zero ODP, and very low direct GWP.

The primary disadvantage of hydrocarbons is flammability, resulting in significant safety and liability issues. This causes increased costs for safety precautions in factories and can necessitate design changes in every application, such as relocation of electrical components to reduce the likelihood of accidents from potential leaks (Kruse, 1996; Paul, 1996). This also entails additional hardware costs for many applications (Dieckmann and Magid, 1999; Crawford, 2000). Hydrocarbon refrigerant use is generally restricted by

U.S. safety codes, and with the exception of industrial refrigeration, the EPA has not listed flammable refrigerants as acceptable substitutes to ODS. EPA will not list flammable refrigerants as acceptable for use in existing motor vehicle air conditioners that were not designed to operate with flammable refrigerants unless such use is supported by a thorough risk assessment. Systems that are designed to use hydrocarbon refrigerants can be listed, but liability concerns remain. Systems using flammable refrigerants will require additional engineering and testing, development of standards and service procedures, and training of manufacturing and service technicians before commercialization. Despite these barriers, several refrigerant blends that contain a small percentage (typically less than five percent) of hydrocarbons, and are therefore not flammable, have been approved for use in motor vehicle air conditioners under EPA's SNAP program. In fact, full implementation of hydrocarbons for use in refrigeration requires fewer technical breakthroughs than carbon dioxide systems (see below). Some companies outside the United States have already begun testing hydrocarbons as refrigerants in automotive applications, and it is estimated that systems with flammable refrigerants could be installed in vehicles in as little as four to five years (Mathur, 1996; Baker, 2000).

Although sufficient information is not yet available to fully assess the feasibility of hydrocarbons in large charge sizes for non-mobile vehicle air-conditioning applications in the United States, hydrocarbon refrigerants are already being used in other countries. One company in the United Kingdom has developed four different blends of hydrocarbon refrigerants (composed of isobutane, propane, and ethane) for use in new household refrigerators and freezers, small commercial refrigeration and air-conditioning systems, as well as commercial air-conditioning and commercial and industrial systems that have traditionally used R-502 or HCFC-22. One Swedish company, the world's largest industrial refrigeration company, is now using these hydrocarbon refrigerants in a full range of hydrocarbon chillers, with over 50 different models already available on the market. The new chillers require 60 percent less refrigerant charge than with HFCs. Similarly, one of Europe's largest refrigerator manufacturers has also converted its U.K. factory to use these hydrocarbon refrigerants, with 12 models of refrigerators, freezers, and refrigerator freezers now on the market. There are now over 30 million hydrocarbon refrigerators in use in Europe (Calor Gas Refrigeration, 2000).

Carbon Dioxide. Another option is to use carbon dioxide as a cooling agent. Carbon dioxide has been investigated for use primarily in mobile air-conditioning systems and refrigerated transport. Carbon dioxide is advantageous for use as a refrigerant because it has zero ODP, a low GWP, and is generally available at a 20 percent greater cost than conventional systems (Hans Hammer of Audi AG, 1998; Baker, 1998).

Carbon dioxide has disadvantages as well, and certain issues such as safety (OSHA's recommended 8-hour time-weighted average is 5,000 ppm), cost of designing and purchasing equipment, potential loss of operational efficiency and the associated increase in indirect emissions, refrigerant containment, long-term reliability, and compressor performance would be of concern (Environment Canada, 1998; ACGIH, 1999).

Transcritical carbon dioxide systems are under study and development by many vehicle manufacturers in co-operation with global component and system suppliers. They require substantial new engineering and testing efforts, with emphasis on reliability testing (Wertenbach, 1996). New equipment and technician training would also be required to safely repair systems with operating pressures up to 6 times higher than systems with HFC-134a. The first systems could be available within four to seven years (Baker, 2000).

Alternative Refrigeration Technologies

Secondary Loop Systems. Secondary loop systems pump cold brine solutions through a second set of loops away from the refrigeration equipment and into areas to be cooled. These systems require a significantly lower refrigerant charge, have lower leak rates, and can allow the use of flammable or toxic refrigerants. Secondary loops may be used in commercial and industrial refrigeration applications, for example, to cool supermarket display cases without circulating toxic or flammable refrigerants throughout the store. The primary disadvantage of the secondary loop system is a loss of energy efficiency. Installers of secondary cooling systems suggest that decreased charge sizes, decreased leak rates, lower maintenance needs, and longer shelf lives can all result in significant cost-savings over time (Bennett, 2000). Indeed, the reduction in size and leak rate of the refrigerant charge could result in a reduced global warming impact, even with the use of fluorocarbon refrigerants. The use of zero GWP refrigerants could result in even lower global warming impacts (Sand *et al*., 1997). Recent work by the EPA's Office of Research and Development is also showing that because the refrigerating fluid does not go through a phase change, temperature control in the refrigerated cases becomes easier. This represents an important advantage over conventional systems since recent regulations on temperature control for refrigerated products such as meat, poultry, and fish have become more stringent. Moreover, recent technological improvements to secondary cooling systems, such as high-efficiency evaporative condensers and display cases with high temperature brines, have increased system efficiency. Such state-of-the art systems are commercially available, but only at a large cost premium (Walker, 2000a,b). Secondary loops also have potential applications in motor vehicle air-conditioning and residential unitary end uses.

Distributed Systems. Distributed systems are most commonly used in retail food refrigeration, but have potential applications in a variety of end uses (e.g., motor vehicle air-conditioning). A distributed system consists of multiple compressors that are distributed throughout the store near the display cases they serve and are connected by a water loop to a single cooling unit that is located on the roof or outside of the store. Refrigerant charges for distributed systems can be smaller than the refrigerant charge used in a comparable traditional direct expansion system. Significant reductions in total global warming impact from current levels might be possible with distributed systems that use HFC refrigerants (Sand *et al*., 1997). Reduced refrigerant charge sizes, in addition to increased energy efficiency associated with such systems, could effectively decrease global warming impacts, even with the use of fluorocarbon refrigerants.

Absorption Chillers. Gas-fired (as opposed to electrically powered) absorption water chillers are sold in the United States and are common in Japan where electricity costs are high and waste energy is available. Although absorption chillers are far less efficient than competitive systems if waste heat is not available, the technology is feasible and, under some economic circumstances, compares favorably with centrifugal chillers using fluorocarbon refrigerants. Market success will be determined by factors such as the relative costs of natural gas and electricity (these units are rarely cost-effective without low natural gas prices or high electricity rates and significant amounts of available waste heat), peak load charges, and purchase costs. In addition, absorption chillers currently have higher capital costs than vapor compression equipment, so significant operating cost savings would be necessary to make their purchase economically competitive. Three United States heating, ventilation, and air-conditioning (HVAC) companies are developing direct-fired, triple-effect absorption concepts that are expected to be 20 to 45 percent more efficient than current double-effect chillers (Sand *et al*., 1997).

Absorption Refrigeration. More than a million thermally-activated ammonia/water absorption refrigerators are manufactured and sold annually worldwide. The refrigerants used for absorption refrigeration have negligible GWP. Absorption refrigeration may become more common in the residential refrigeration end use as ozone-depleting substances are phased out. Absorption refrigeration is commonly used in hotel rooms and for recreational vehicles because it operates quietly and has the ability to use bottled gas as an energy source. Absorption refrigerators are limited in size because of design constraints. The thermal coefficient of performance (COP) of these refrigerators can be increased by as much as 50 percent (from a COP of 0.2 to 0.3) through design improvements without degrading cooling capacity (Sand *et al*., 1997). Low efficiency and inherent design limitations make it unlikely that absorption refrigeration will become a significant replacement for vapor compression refrigerators. However, absorption refrigeration has great capacity and operating attributes that permit it to fill niche markets (Sand *et al*., 1997).

Absorption Heat Pumps. Research and development efforts are attempting to create absorption heat pumps that would be used for heating and cooling in residential and light commercial applications. In Europe and the United States, generator absorber heat exchange (GAX) ammonia-water absorption heat pumps are being developed, while field test units have been built in Japan. Absorption heat pumps could be used to reduce global warming impacts in areas where heating load dominates, although they would have the opposite effect in areas where cooling dominates (Sand *et al*., 1997).

Desiccant Cooling. Desiccant cooling is produced by removing moisture from an air stream using a desiccant, and then separately cooling the dry air. The desiccant is thermally regenerated, typically by burning natural gas or alternatively, by capturing excess heat. Desiccant cooling may replace the latent cooling done by some equipment end uses, such as chillers and motor vehicle air-conditioners. Integrated desiccant cooling systems that combine a desiccant system with a vapor compression or other cooling systems have been successfully installed in some commercial buildings (Fisher *et al*., 1994). Current designs are used primarily in niche markets that require precisely-controlled and/or low humidity, such as supermarkets and hospital operating rooms. For desiccant-based systems to be considered feasible options in the commercial air-conditioning market, improvements in efficiency, cost, size, reliability, and life expectancy must be made (Sand *et al*., 1997).

Desiccants require an intermittent source of heat. Because new automobiles are energy efficient, very little waste heat is produced. While an automobile is not moving in traffic or is driven slowly, not enough heat may be produced for a desiccant system to function. Desiccant systems may therefore only be feasible where there is a large heat source, as in a large truck or bus (Environment Canada, 1998). In order for desiccant air-conditioners to become viable options for motor vehicle air-conditioning, it must be demonstrated that adequate waste heat is generated during vehicle operation to drive the system, or an auxiliary burner must be made available when additional heat is required. Current prototypes are large and heavy, such that the desiccant air-conditioning systems must be reduced in size and weight and it must be shown that the systems are durable and can have a service life long enough to justify the initial investment. Finally, costs need to be competitive with HFC compression air-conditioning systems (Fisher *et al*., 1994).